Flow and Regime Dependent Mesoscale Predictability

Principal Investigator: Dr. Fuqing Zhang
Department of Atmospheric Sciences, Texas A&M University, College Station, Texas 77843
[Now also employed as Professor of Meteorology, The Pennsylvania State University]
Phone: 814-865-0470 fax: 814-865-0478 email: fzhang@psu.edu

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LONG-TERM GOALS

The ultimate goals of the proposed work are to estimate the predictability of mesoscale features embedded within different synoptic-scale flow regimes and to identify key physical processes that control the limit of predictability at the mesoscale through explicit simulations of idealized moist baroclinic waves and case studies of high-impact weather events.

OBJECTIVES

Major objectives of the original YIP project include: (1) determine key dynamical differences in the flows that lead to different mesoscale error growth dynamics in different high-impact weather events; (2) generalize results of flow-dependent mesoscale predictability concluded from real case studies through explicit simulations of idealized moist baroclinic waves; (3) explore differences between warm-season and cold-season, and between tropical and extratropical error-growth dynamics; and (4) synthesize flow-dependent mesoscale error growth dynamics with conceptual models. Our working hypothesis, a multistage conceptual model, is that moist processes impose fundamental limits on mesoscale predictability but the error-growth dynamics is strongly dependent on the larger-scale background flow and its attendant dynamics.

Additional objectives in the expansion project for the past year builds on the success of the original YIP support but expand the research into additional new directions: (1) help transitioning a mesoscale ensemble data assimilation system developed by the PI's team to COAMPS; (2) extend understanding of mesoscale predictability of extratropical weather systems to those of tropical convection and tropical cyclones cloud-resolving mesoscale modeling systems; and (3) improve tropical cyclone track and intensity prediction through further development of the regional-scale, cloud-resolving ensemble-based data assimilation and prediction system capable of efficiently assimilating ground-based and airborne Doppler observations and satellite derived products.

APPROACH

Since the beginning of the project, three graduate research assistants (Andrew Odins, Dan Hawblitzel and Jason Sippel), two postdoctoral research associate (Drs. Naifang Bei and Shuguang Wang) and a visiting scientists (Dr. Juan Fang) have been fully or partially trained/sponsored by this project. Odins completed and defended successfully his master's thesis in the fall of 2004 on the mesoscale predictability of an extreme warm-season south-central Texas flooding event of June-July 2003 (Odins 2004; Zhang et al. 2005). Hawblitzel completed and defended successfully his master's thesis on the

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14. ABSTRACT
The ultimate goals of the proposed work are to estimate the predictability of mesoscale features embedded within different synoptic-scale flow regimes and to identify key physical processes that control the limit of predictability at the mesoscale through explicit simulations of idealized moist baroclinic waves and case studies of high-impact weather events.

15. SUBJECT TERMS

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impact of moist convection on the predictability of a long-lived mesoscale convective event of 10-13 June 2003 (Hawblitzel 2005; Hawblitzel et al. 2006). In August 2008, Sippel completed and successfully defended his Ph.D. dissertation on the dynamics and predictability of tropical cyclones using ensemble forecasts, especially formed near the coastal areas of the United States and Western Pacific Regions.

Dr. Bei worked on several areas of the project including (1) mesoscale predictability of the Storm of the Century of March 1993 ("SOC") and its comparison to another well-studied cold-season event, the 'surprise' snowstorm of January 2000; (2) mesoscale predictability of warm-season torrential rainfall events along the Meiyu fronts in China; and (3) mesoscale predictability of idealized moist baroclinic waves with high-resolution simulations and diagnosis which contributes significantly to the synthesis of conceptual mesoscale error growth model. Dr. Bei left the project for another position in 2006.

Drs. Wang and Fang have been working the dynamics and predictability of different hurricanes (e.g., Katrina 2005 and Dolly 2008) through experiments with and without ensemble assimilation of airborne Doppler radar observations. Dr. Fang also examines the impact of vertical wind shear and beta-gyre effect on the development of tropical cyclones. Dr. Wang examines the dynamics and impacts of smaller-scale meso-vortices and/or gravity waves embedded in the hurricane eyewall.

The PI, Dr. Fuqing Zhang, has been actively working on and coordinating all aspects of the project. We are actively collaborating with Dr. Allen Zhang at NRL in transferring the ensemble based data assimilation system to the Navy mesoscale forecast model (COAMPS), with Dr. Craig Bishop at NRL in designing better data assimilation techniques and background error covariance that have the potential to improve the Naval numerical prediction models, and with Dr. Peter Black at NRL/SAIC on the observing system design for hurricanes. We have also collaborated closely with Drs. Zhe-Min Tan (Nanjing University), Craig Epifanio (Texas A&M), Chris Snyder (NCAR) and Rich Rotunno (NCAR) on idealized simulations and predictability of moist baroclinic waves as well as with Drs. Chris Davis, Morris Weisman (NCAR) and John Nielsen-Gammon (Texas A&M) on the warm-season predictability of high-impact events. We also collaborating with Drs. Frank Marks, John Gamamche, Sim Aberson and Altug Aksoy (NOAA/HRD) in assimilating airborne Doppler observations in hurricane prediction models.

For the first objective in examining the mesoscale predictability of the "SOC" and its comparison to the "surprise" snowstorm, we performed experiments identical to those in Zhang et al. (2003). We also examine sensitivity for both cases by introducing perturbations at different stages of the cyclogenesis.

The MM5-based procedure developed in Tan et al. (2004) is used to create balanced initial conditions for simulating idealized moist baroclinic waves. This procedure includes using 3-dimensional potential vorticity (PV) inversion technique to invert the balanced finite amplitude baroclinic waves from specification of the background 3-D PV field. We further extended the low-resolution results from Tan et al. (2004) to convective-resolving simulations.

To further explain the difference of error growth found between the two observed cases and to explore factors other than moist convection and background baroclinicity in limiting mesoscale predictability in a controlled environment, we will extend our idealized predictability study of Tan et al. (2004) through explicit simulations of moist baroclinic waves by (1) introducing surface/boundary layer inhomogeneities, (2) adding perturbations at difference phase of the cyclogenesis, (3) adding

background barotropic shear to the initial baroclinic jet, and/or (4) constructing more realistic configurations with different initial baroclinic and static stabilities.
For the warm-season Texas flooding event of 2002 (Nielse-Gammon et al. 2005; Zhang et al. 2006), we performed high-resolution sensitivity experiments initialized at two different times per day. Little changes in the synoptic flows through the 8-day event allow us to examine/generalize the role of CAPE variation, diurnal cycle and cold pool dynamics in modulating and limiting short-range mesoscale predictability of such an extreme warm-season flooding event. We further expands the study of warm-season predictability to other cases over the continental US (Hawblitzel et al. 2007; Meng and Zhang 2008a,b) and over China (Bei and Zhang 2007).

We also extend the study of mesoscale predictability into tropical cyclones focusing on several recent events: Tropical Storm Allison (2001), "would-be" Alex (2004), Hurricanes Katrina (2005) and Humberto (2007) and Typhoon Bilis (2006) [Sippel and Zhang 2008; Zhang and Sippel 2008; Zhang et al. 2008; Sippel 2008].

We successfully implemented the ensemble analysis and prediction system in realtime to assimilate airborne radar observations which demonstrated great potential in recent storms of Hurricane Gustav and Ike (2008). Through ensemble simulations and sensitivity experiments, we aim to examine the flow- and regime- dependent predictability of tropical cyclones. We also examined the impact of uncertainty on the public response to hurricane forecasts.

We examined both the intrinsic and practical aspects of mesoscale predictability in which realistic and/or small amplitude errors in both the forecast model and initial conditions are considered. Four forms of idealized initial perturbations as a function of initial spatial scales are tested: (1) a monochromatic small-scale wave as in Zhang et al. (2003); (2) "grid-point" random noises with energy equally projected to all scales as in Tan et al. (2004); (3) large-scale random but balanced initial errors through inversion of the randomly-perturbed geostrophic streamfunction in the WRF/MM5 3Dvar system; and (4) ensemble perturbation generation through an ensemble-based mesoscale data assimilation system (Zhang et al. 2006a).

For quantitative evaluation of error evolution, we continue to use the diagnostics developed and implemented in our previous studies (Zhang et al. 2002, 2003; Tan et al. 2004) which include tracking difference energy growth between forecasts and performing spectral analysis of the difference energy.

WORK COMPLETED

We make significant progress in the objectives proposed for the YIP expansion. The transition of the ensemble data assimilation to the COAMPS is well underway thanks for the leading effort by Dr. Allen Zhao at NRL. We begin to make significant progress in understanding the dynamics and predictability of tropical cyclones and in designing better approaches for hurricane initialization.

RESULTS

There are a total of **16** journal publications directly sponsored by this project including **16** in print or in press (Tan et al. 2004; Zhang 2005; Nielsen-Gammon et al. 2005; Zhang et al. 2006a; Zhang et al. 2006b; Hawblitzel et al. 2007a; Meng and Zhang 2007; Bei and Zhang 2007; Zhang et al. 2007b; Zhang et al. 2007c; Zhang et al. 2008a; Meng and Zhang 2008a; Meng and Zhang 2007b; Sippel and Zhang 2008; Morss and Zhang 2008) and **4** in different stages of the peer-review process (Zhang and

Sippel 2008; Gao et al. 2008; Zhang et al. 2008b; Jun et al. 2008). Highlights of the work completed during the past year are listed below:

(1) Mesoscale dynamics and predictability of tropical cyclones and hurricanes (Zhang and Sippel 2008; Sippel and Zhang 2008; Sippel 2008; Gao et al. 2008; Fang and Zhang 2008): Probabilistic methods developed in Hawblitzel et al. (2007) are used to investigate the genesis dynamics and predictability of Hurricane Humberto (2007), a null case in which the MM5 predicted a tropical cyclone that never formed in late July 2004. Ongoing work also explores the predictability of Typhoon Bilis (2006), a Western Pacific storm that produced record-breaking, catastrophic rainfall all across southern China. It is found that at least for some cases, the predictability of tropical cyclones may ultimately be limited by the randomness of moist convection. However, there are key differences between predictability of mid-latitude and tropical weather systems due to differences in the large-scale environment (e.g., baroclinic/barotropic instability and air-sea interaction, CAPE, shear, surface heat fluxes, and WISHE) as well as internal dynamics (e.g., the time and spatial scales of convective and geostrophic adjustment, Rossby radius of deformation, and vortex Rossby waves).

(2) *Improve tropical cyclone track and intensity prediction through further development of the regional-scale, cloud-resolving ensemble-based data assimilation and prediction system capable of efficiently assimilating ground-based and airborne Doppler observations and satellite derived products.* We examined the performance of the ensemble-based data assimilation system for several high impact historical cases with Doppler radar observations that includes Hurricanes Katrina (2005), Emily (2005) and Rita (2005) and Humberto (2007); we also applied the system in realtime or near-realtime for several of the 2008 storms (Dolly, Fay, Gustav and Ike). In all these cases, it is found that the ensemble analysis and forecast system with Doppler observations assimilated can significantly improve the track/intensity prediction while reveal significant uncertainty in the forecast. An example of the system performance of Hurricane Humberto (2007) with ground-based radar observations is shown in Figures 1 and 2.

(3) *Transitioning the mesoscale ensemble data assimilation system to COAMPS.* This system was originally developed by the PI partially funded by the YIP grant capable of assimilating in-situ and remote observations including radar data. The initial tests of the COAMPS-based system at NRL by Dr. Allen Zhao were very encouraging and we will continue to improve it for the Navy model.

IMPACT/APPLICATIONS

Understanding of the limit of mesoscale predictability and the associated error growth dynamics is essential for setting up expectations and priorities for advancing deterministic mesoscale forecasting and for providing guidance on the design, implementation and application of short-range ensemble prediction systems. Understanding the nature of mesoscale predictability is also crucial to the design of the efficient data assimilation systems for the meso- and regional scales and hurricanes. The advanced ensemble-based data assimilation system which is capable of assimilating both ground and airborne Doppler radar observations is very promising for the future cloud-resolving mesoscale prediction.

The PI Professor Fuqing Zhang has been awarded the 2009 Clarence Leroy Meisinger Award for "for outstanding contributions to mesoscale dynamics, predictability, and ensemble data assimilation", the highest honor given by the American Meteorological Society to young, promising atmospheric scientists who have recently shown outstanding ability and are under 40 years of age when nominated. The ONR/YIP is one of the primary sponsors that support his award-winning research.

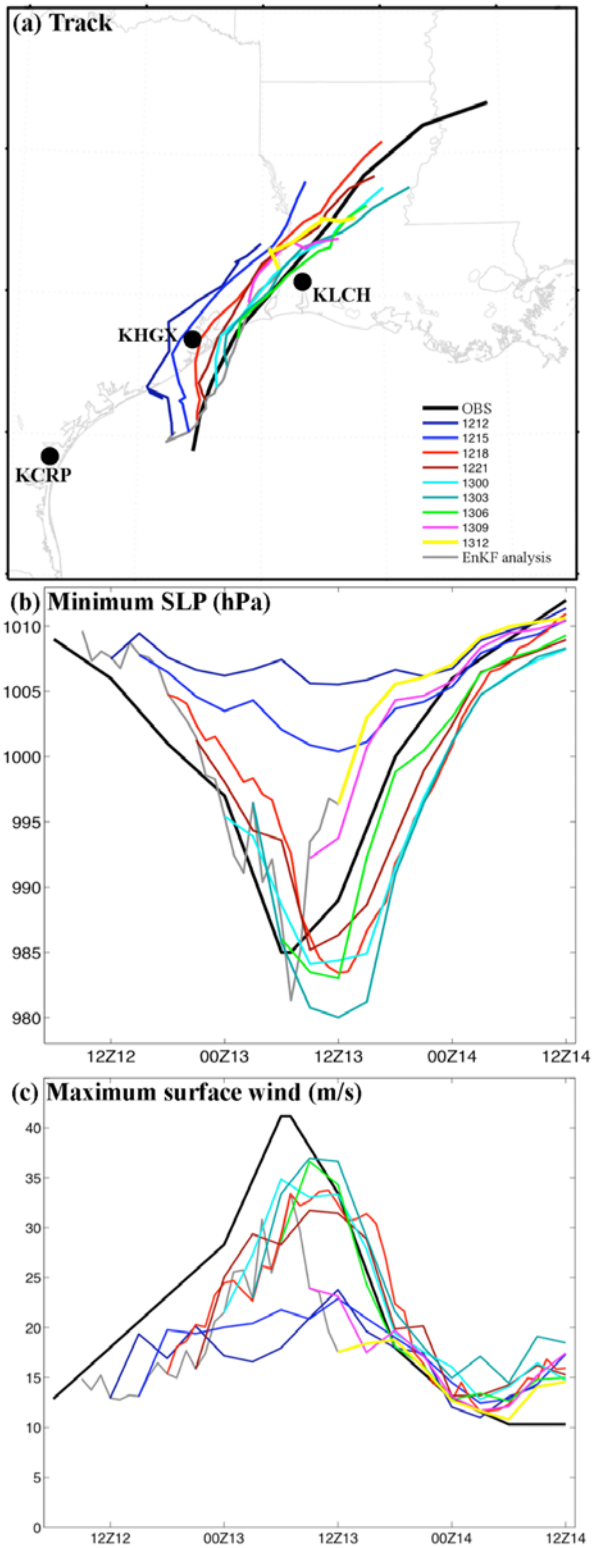

FIG 1. The simulated (a) positions, (b) minimum SLP and (c) maximum surface wind of Hurricane Humberto (2007) in the deterministic WRF forecasts (color curves) initialized with the EnKF assimilation of NEXRAD radar observations every hour from 09Z/12 to 12Z/13 in comparison with the NHC best track estimate (black).

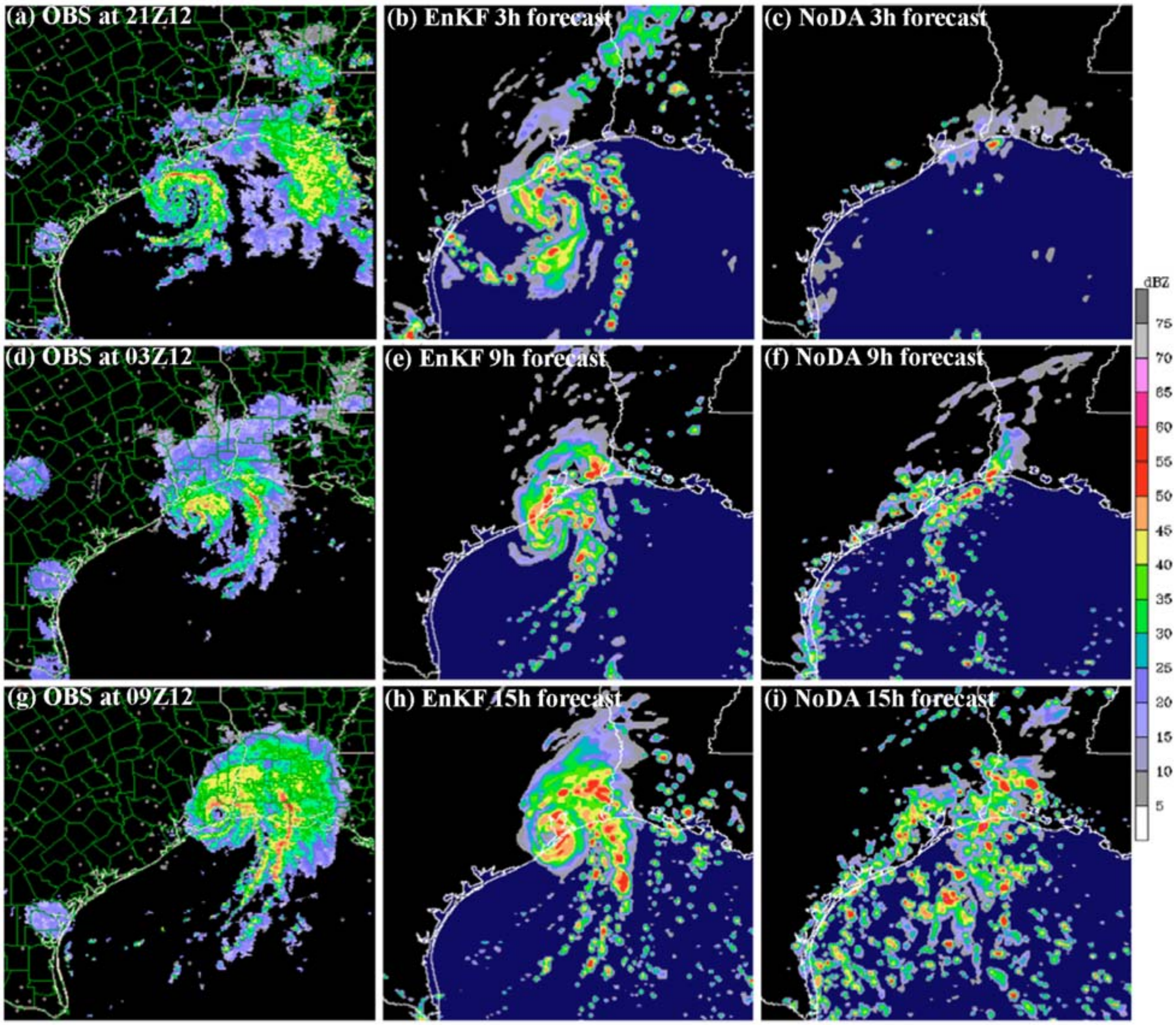

FIG 2. Comparison of radar reflectivity (dBZ) from observational composite mosaics (OBS; left panels), the deterministic forecast initialized with the EnKF analysis at 18Z/12 (middle panels), and with the NoDA ensemble forecast mean (right panels) valid at 21Z/12, 03Z/13 and 09Z/13, respectively.

TRANSITIONS

In collaborations with scientists at NRL Monterey, the WRF-based ensemble data assimilation system partially sponsored by this project is currently being transplanted to the Navy mesoscale prediction model COAMPS with the potential to be used in future operational forecasts.

The ensemble-based data assimilation system is also currently being transitioned to the Hurricane Research System (HRS model) at the Hurricane Research Division of NOAA.

RELATED PROJECTS

Collaborative Research: Ensemble-based State Estimation for Weather Research and Forecast Model.

<u>National Science Foundation (NSF); 09/01/02-08/31/08; $295,000; Fuqing Zhang (Principal Investigator).</u> The NSF sponsored project closely related to this project because mesoscale predictability and data assimilation are two integral parts of state estimation. Data assimilation provides better initial condition to assess predictability while predictability points to the ultimate benefits and limitations of data assimilation.

<u>Dynamics and Impacts of Mesoscale Gravity Waves. National Science Foundation (NSF); 09/15/02-02/28/07; $224,834; Fuqing Zhang (Principal Investigator) and "Dynamics and Impacts of Mesoscale Gravity Waves from Baroclinic Jet-Front Systems". National Science Foundation (NSF); 11/01/06-10/31/09; $399,961; Fuqing Zhang (Principal Investigator). Both</u> NSF sponsored projects are closely related to this project because gravity wave dynamics and geostrophic adjustment play an important role in understanding the upscale growth of error energy from moist convection which limits to limit of mesoscale predictability.

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Note: there are more than 30 conference presentations reporting results fully or partially sponsored by this project including ~15 of them over the past year alone (detail list of the conference abstracts is omitted for brevity).